

# Galactic Diffuse $\gamma$ -ray Emission at TeV Energies and the Ultra-High Energy Cosmic Rays

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**Abstract.** Using the cosmic ray (CR) data available in the energy interval  $(10 - 2 \times 10^7)$  GeV/particle, we have calculated the profile of the primary  $\gamma$ -ray spectrum produced by the interaction of these CR with thermal nuclei of the ISM. Normalized to the EGRET measurements, this allows an estimate of the galactic diffuse  $\gamma$ -ray background due to intermediate and high energy CR at TeV energies. On the other hand, over the last few years, several particles with energies above  $10^{20}$  eV (beyond the Greisen-Zatsepin-Kuzmin cut-off) have been detected. These particles are very likely extragalactic protons originated at distances not greater than  $30 - 50$  Mpc [e.g., 1]. The propagation of these ultra-high energy protons (UHEP) through the intergalactic medium leads to the development of  $\gamma$ -ray cascades and an ultimate signature at TeV energies. To assess the statistical significance of this  $\gamma$ -ray signature by the UHEP, we have also simulated the development of electromagnetic cascades triggered by the decay of a  $10^{19}$  eV  $\pi^0$  in the intergalactic medium after an UHEP collision with a cosmic microwave background photon.

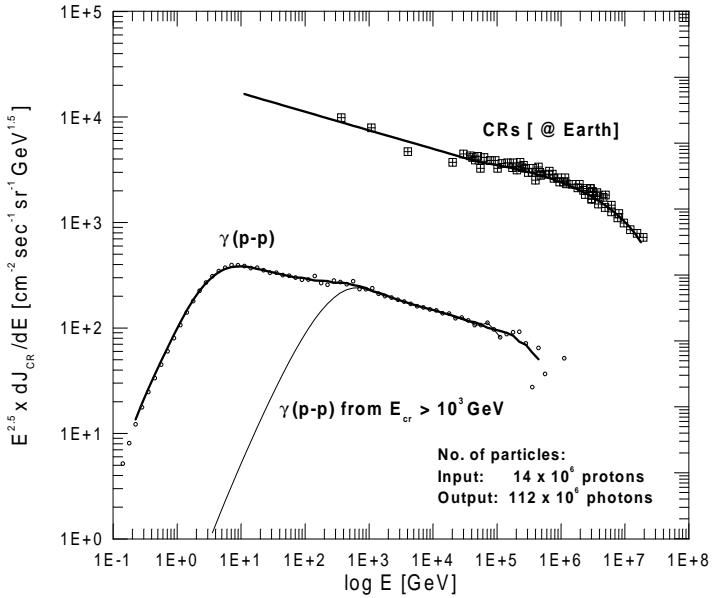
## THE $\gamma$ -RAY SPECTRUM AT $10^{12} - 10^{15}$ EV

The  $\gamma$ -ray production mechanisms related to CR interactions with the ISM are well understood and have been described in detail by a number of authors [e.g., 2]. The processes which contribute to diffuse  $\gamma$ -ray production are: (i) bremsstrahlung; (ii) inverse Compton scattering; and (iii) nuclear interactions, but for the energies of interest in the present work, which are above 10 GeV, the latter is the most relevant mechanism.

In order to calculate the  $\gamma$ -ray differential spectrum,  $dN_\gamma/dE$ , from the observed CR differential spectrum,  $dJ_{cr}/dE$ , we have employed the *Lund Monte Carlo for Hadronic Processes* routines (PYTHIA version 6.1, March 1997) [3]. The CR energy

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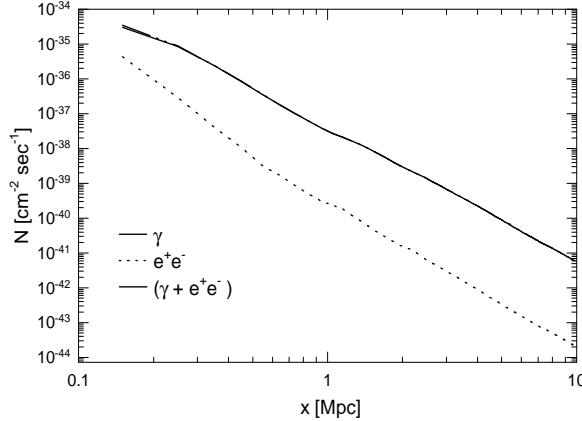
**FIGURE 1.** Observed CR spectrum (obtained from BASJE, TIBET, TACT, TUNKA, JACEE and Grigorov experiments), and the calculated background  $\gamma$ -ray spectrum at TeV energies.

spectrum includes data from BASJE, TIBET, TACT, TUNKA, JACEE and Grigorov [4]. CR nuclei interact with the ISM thermal nuclei producing  $\gamma$ -ray through different processes (e.g.,  $\pi^0 \rightarrow 2\gamma$ ;  $\pi^+ \rightarrow \mu^+ \rightarrow e^+ \rightarrow \gamma$ ;  $q\bar{q} \rightarrow g\gamma$ ;  $f\bar{f} \rightarrow \gamma\gamma$ ;  $qg \rightarrow q\gamma$ ; etc). The resulting  $\gamma$ -ray spectrum is depicted in Fig. 1.

The evaluation of the mean-free path of the  $\gamma$ -ray photons through the galactic background radiation field (stellar, IR, and cosmic microwave background (CMB) photons) shows that the primary  $\gamma$ -spectrum at  $E_\gamma \simeq (10^{10} - 10^{15})$  eV is almost unaffected by interactions with background photons [5]. Therefore, the actual value of the galactic  $\gamma$ -background at these energies can be estimated by normalizing the  $\gamma$ -spectrum of figure 1 to the EGRET observations at 1-10 GeV.

## ELECTROMAGNETIC CASCADES DUE TO UHEP

For the analysis of the electromagnetic cascading triggered by UHEP propagation through the intergalactic medium (IGM), two different situations must be considered: (i) when an intergalactic magnetic field is present ( $B_{IGM} \neq 0$ ); or (ii) when it is absent (e.g., inside the voids) ( $B_{IGM} \simeq 0$ ). In the first case, synchrotron radiation will prevent the development of cascading due to the rapid draining of energy of the secondary electrons into low energy photons

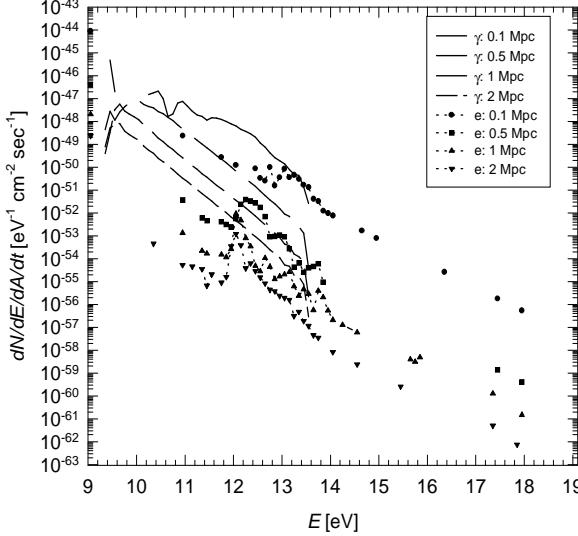


**FIGURE 2.** Total flux of  $\gamma$ -ray photons and electron-positron pairs [ $cm^{-2} s^{-1}$ ] produced in a cascade triggered by a  $10^{20}$  eV proton as a function of the distance along the axes of the cascade ( $x$ ).

$$E_\gamma \approx 2 \times 10^{11} \left( \frac{B_\perp}{10^{-9} G} \right) \left( \frac{E_e}{10^{20} eV} \right)^2 eV \quad (1)$$

Moreover, for the  $\approx 10^8$  photons produced, relativistic beaming and curvature of the electron's trajectory will reduce to only  $\sim 2 \times 10^{-3}$  the number of photons that can be detected per event, per observer [5]. Thus, we must focus on the case for which  $B_{IGM} \simeq 0$ . In this case, the cascade is initiated by the interaction of an UHEP with a photon of the CMBR. Either a neutral or a charged pion may be produced and the initial energy is subsequently channeled to lower and lower energies through a  $\gamma\gamma$ -pair production, inverse Compton cycle [6], until no further  $\gamma$ -ray is produced when then the threshold for pair production due to interactions with the CMBR photons is reached. Thereafter, the interactions must involve higher background photons and the corresponding mean-free path,  $\lambda_{\gamma\gamma}$ , increases rapidly [see, e.g., 7-8].

As an example, Figs. 2-4 show the results for a typical cascade triggered by a  $10^{20}$  eV UHEP while traversing a very low magnetic field ( $B \lesssim 10^{-12}$  G) region of the IGM.



**FIGURE 3.** Spectra of  $\gamma$ -ray photons and electrons [ $eV^{-1} s^{-1} cm^{-2}$ ] produced in a cascade triggered by a  $10^{20}$  eV-proton for different distances  $x$ .

## CONCLUSIONS AND DISCUSSION

The previous results indicate that, as soon as the shower effectively develops (i.e., at  $d \gtrsim 100$  kpc, from the  $\pi^0$  decay), low energy electrons are produced. Consequently, an upper limit for the duration of the cascade at the detector can be calculated as the time delay between a  $10^{12}$  eV electron and a  $\gamma$ -ray photon [ $\Delta t \approx (1 - \beta)d/c$ ]:

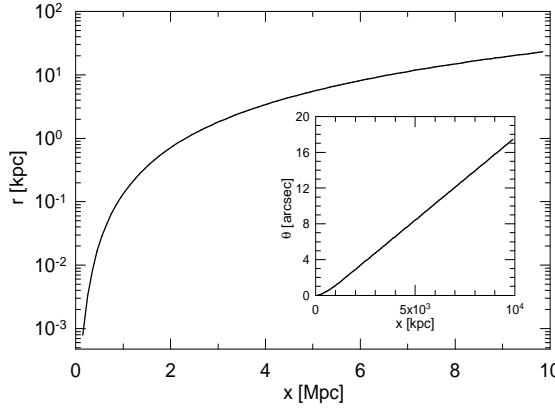
$$\Delta t \simeq 0.1 \left( \frac{d}{1 Mpc} \right) s \quad (2)$$

The results above also indicate that a cascade initiated by a single UHEP interaction with CMB photons should reduce to, at most, one photon of relatively low energy at the detector (see [5] for details). This renders the UHEP-CMB photon interaction practically unobservable.

The situation turns out to be different if one considers the background of  $\gamma$ -rays produced by the whole distribution of UHEP interacting with the CMBR

$$F_{obs}(r) = \frac{\pi \nu_{p,\gamma}}{4} \int_0^r \theta(r)^2 \Phi(r) \Delta t(r) r^2 dr \quad (3)$$

Where  $\nu_{p,\gamma}$  is the number of UHEP- $\gamma_{CMB}$  interactions per unit time, per unit volume. Since the estimated flux of UHECR is  $J(E > 10^{20}) \text{ eV} \approx 3.3 \times 10^{-21} \text{ cm}^{-2}$



**FIGURE 4.** Radius ( $r$ ) and aperture angle ( $\theta$ ) of the cascade in the laboratory reference frame as a function of the distance along the cascade axes ( $x$ ).

$sr^{-1} s^{-1}$  [9],  $\nu_{p,\gamma} \approx 10^{-45} cm^{-3} s^{-1}$ . Considering the volume of the local Universe within which the UHECR sources must be located ( $d \lesssim 50$  Mpc), we derive a lower limit for the contribution of UHECR to the background diffuse  $\gamma$ -ray flux  $F_{obs} \approx 10^{-10} cm^{-2} s^{-1}$ . This value is about an order of magnitude smaller than the galactic diffuse background as estimated from our calculations and from the EGRET data [5]. Nonetheless, this contribution is comparable to the  $\gamma$ -ray diffuse background component due to blazers (see, e.g., Fegan, this conference [10]).

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